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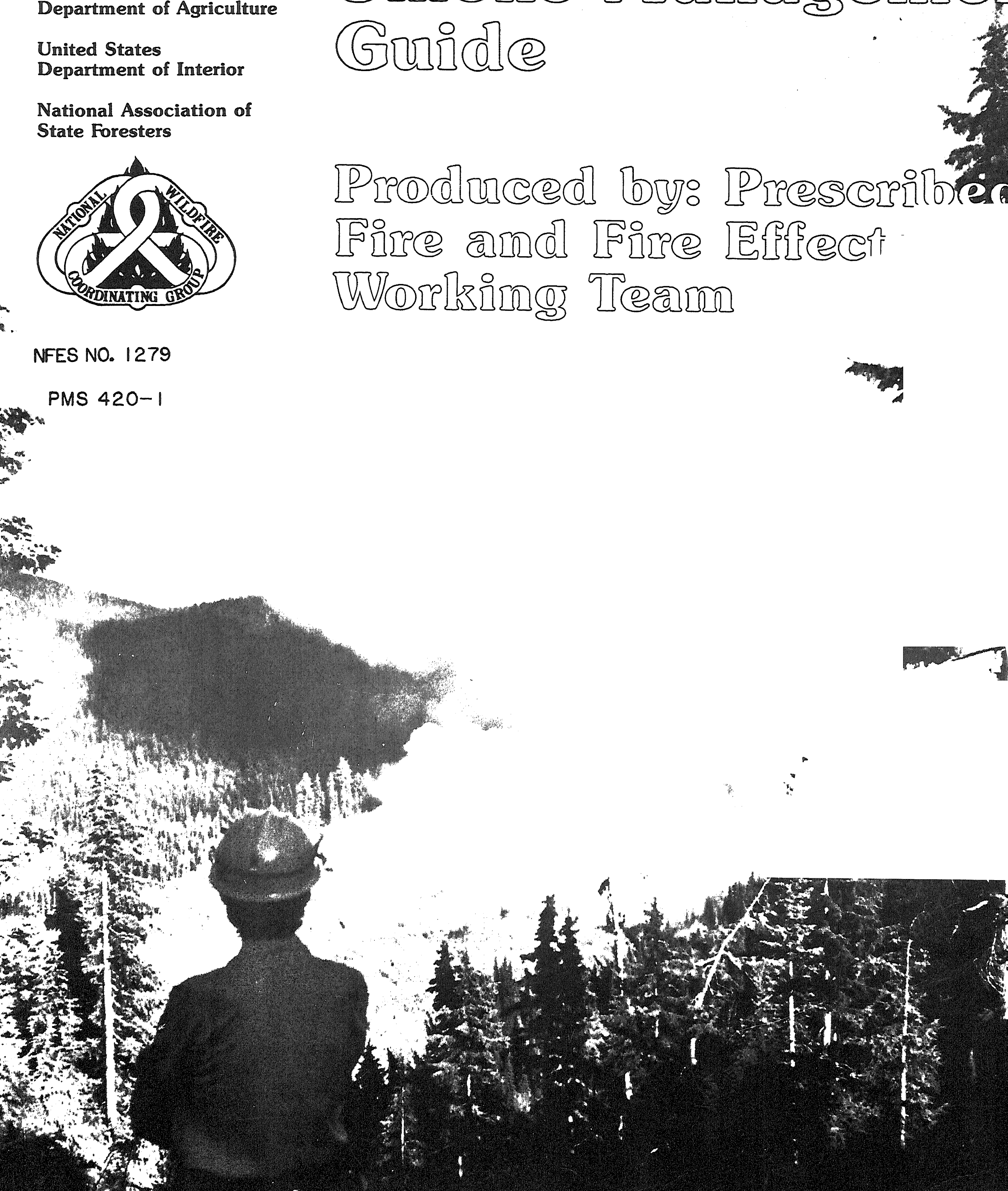
Smoke Manageme
Guide

Produced by: Prescrib
Fire and Fire Effect
Working Team



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PRESCRIBED FIRE

SMOKE MANAGEMENT GUIDE
Produced by: Prescribed Fire and Fire Effects Working Team

FEBRUARY 1985

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SMOKE MANAGEMENT GUIDE

INTRODUCTION

This publication provides guidelines for planning and managing smoke from prescribed fires to achieve air quality requirements through improved smoke management practices. The Guide focuses on national smoke management principles; however, for maximum use and effectiveness, local users should prepare regional and local supplements. The Guide applies to all prescribed fires, those started by nature and by managers, and its use is not limited to any one agency or region.

When planning and conducting prescribed fires, the Prescribed Fire Manager and Prescribed Burn Boss must exercise their responsibilities in a way that meets Clean Air Act standards (Public Law 95-95) and best serves the public interest. Prescribed fire stewardship emphasizes the immediate safety aspects of personnel conducting the burn; the health, safety, and property of others that may be directly affected by the fire; and the potential for off-site effects of smoke on public health and visibility. We emphasize, however, that the Prescribed Fire Manager and Prescribed Burn Boss cannot merely comply with standards and regulations; they must look beyond compliance and exercise professional and moral judgment in carrying out their duties.

Central to the acceptance of prescribed fire management by State and local air quality authorities, and the public is the way we handle smoke management responsibilities. Prescribed fires produce varying quantities of smoke, an elusive by-product which can be a major concern; therefore, smoke management must be considered in every prescribed fire plan. However, we do not want to leave the reader of this Guide with the impression that all smoke is bad. Too often we get trapped into this kind of thinking and we attempt to solve one problem only to find we have created another. Fire and resultant smoke is an integral part of many ecosystems and cannot be separated from these ecosystems without some consequence. Awareness of smoke production and transport characteristics will enable us to refine existing smoke management prescriptions and develop new ones. This guidebook addresses methods for avoiding or mitigating the adverse impacts of smoke on human health and welfare. An understanding of smoke management principles and their application promotes better public understanding and reduces adverse impacts on air quality.

The Prescribed Fire Smoke Management Guide can be used at various levels of an organization. The Prescribed Fire Manager and Resource Specialists will find the Guide important in assuring that prescribed fire programs will meet smoke management and air quality objectives. The Prescribed Burn Boss can use the Guide to develop techniques to meet smoke management objectives for individual prescribed fires. The Guide can also be an important background document for developing a public awareness program. The public in general is unaware of smoke management programs. Informing them about the many prescribed fires that do not create smoke incidents will make them more likely to tolerate an occasional smoke intrusion.

This Guide covers smoke management objectives and regulatory requirements, smoke production, smoke management, and smoke monitoring and evaluation.

The lead author for each chapter served as the chapter's primary author in addition to serving on the Prescribed Fire and Fire Effects Working Team's steering group. The names of additional authors appear in alphabetical order. The Prescribed Fire and Fire Effects Working Team conceived the idea, developed the objectives and outline, wrote the introduction, and edited and published the Guide.

Chapter I.

Smoke Management Objectives and Regulatory Requirements

Stan Coloff, James Byrne, Marshall Mott-Smith, Michael Rogers

General Objectives of Smoke Management

This chapter introduces the general objectives of smoke management as it affects air quality, the Clean Air Act, and State and local regulations that implement the Clean Air Act.

The three basic objectives of smoke management are:

1. Identify and avoid smoke-sensitive areas.

2. Reduce emissions.

3. Disperse and dilute smoke before it reaches smoke-sensitive areas.

These objectives are achieved through technology and strategies that minimize damage to air quality and visibility that is caused by prescribed fires.

How well we manage smoke from prescribed fires will determine our future use of this tool. Poor smoke management can cause health and safety problems in inhabited areas. Land managers have been held liable and paid for damages caused by smoke from planned ignitions that impaired visibility causing traffic accidents, property damage, injuries, and fatalities.

The key to good smoke management lies in the land manager's ability to use prescribed fire with minimal smoke impact; this is done by combining favorable meteorological conditions with a variety of prescribed fire techniques designed to keep smoke emissions to a minimum (see Chapter III).

An active public information program will improve public understanding and acceptance of the need for prescribed fire and smoke management. This is especially critical in smoke-sensitive places such as urban and rural population centers, hospitals, major transportation facilities (airports, highways), and recreational areas, where smoke can negatively affect safety, health, and aesthetics.

Overview of The Clean Air Act

Congress passed the Clean Air Act (1967) and amendments to the Act (1972, 1977) to protect and enhance the quality of the Nation's air resources and to protect public health and welfare. The Act established National Ambient Air Quality Standards and gave the States primary responsibility for air quality management. States carry out this responsibility through a State Implementation Plan (SIP), which is developed at the State level. How States achieve and maintain applicable Federal and State standards is described in the State Implementation Plan (SIP). Some State regulations pertaining to air quality are administered by more than one State agency, thus not all air regulations may be found in the SIP. Therefore, it may be necessary to contact other state or local agencies. Federal and State land managers must be certain that their actions comply with all procedural and substantive requirements contained in Federal, State, and local air pollution control regulations. The Clean Air Act requires States to identify nonattainment areas (areas which do not meet national air quality standards) and to take specific action to bring those areas into compliance. Specific plans to reduce emissions and bring the area into compliance become part of the SIP. Through this mechanism, to achieve compliance, States and local air quality authorities can reduce or eliminate the use of prescribed burning in an area designated as nonattainment for particulates. This requirement could also restrict the use of prescribed fire outside a nonattainment area if such fires would contribute to the particulate load within a nonattainment area.

The Clean Air Act also provides for prevention of significant deterioration (PSD) of air quality. The basic intent of this provision is to limit degradation of air quality particularly in those areas of the country where the air quality is much better than standards. In Class I areas only a very small amount or increment of air quality deterioration is permissible. Class I areas include specified national parks, wilderness areas, and certain Indian reservations. The remainder of the country is designated Class II. The PSD permit provisions of the Act apply only to major stationary sources of air pollution, such as power plants, and do not include prescribed fire which is defined as a temporary source.

Protection of visibility in Class I areas is an important aspect of the PSD section of the Clean Air Act. The Act explicitly sets a broad national goal to prevent any future impairment of visibility in Class I areas and to remedy any existing impairment from human-caused air pollution. Although prescribed fire is defined as a temporary source of air pollution we must recognize that the national goal for visibility protection is broad enough to eventually regulate the use of prescribed fire.

Particulate matter *(visible smoke)* is regulated through an ambient air quality standard. The present standard for Total Suspended Particulates (TSP) covers a large range of particle sizes typically from 0 to 50 micrometers (um) (50 millionths of a meter); about half the thickness of a human hair. Over ninety percent of smoke particles are less than 10 um. A proposed particulate standard aimed more at regulating inhalable particles, known as PM-10, focuses on the size range of particles of primary concern to human health. With respect to prescribed fire emissions and the proposed PM-10 standard, smoke management practices provide the most practical and effective means of achieving the Clean Air Act objectives of protecting public health and welfare. It is important to realize that any final PM-10 standard will apply in all areas where the public has access, not just in smoke sensitive areas.

The question often arises, *"Will I be in violation of the Clean Air Act if smoke from my prescribed fire enters a Class I area?"* This question cannot be answered directly in terms of the Clean Air Act alone because states have the authority to set tighter standards or establish regulations which could limit or prohibit smoke intrusions into Class I areas. Although the Clean Air Act does not specifically address smoke as an air pollutant, it does provide the states with the responsibility and authority to establish regulations to deal with smoke. More important, states are required by the Act to achieve the National Air Quality Standards. To meet these standards, smoke and prescribed fires can be regulated. Some States are considering regulations to restrict intrusions of smoke from prescribed fires into Class I areas and other smoke-sensitive areas.

Prescribed Fire Managers must remain knowledgeable about applicable State/local laws and coordinate with air quality and smoke management officials regarding smoke impacts in sensitive areas. It is equally important for prescribed fire managers to voice their concerns and actively participate in State and local rule making.

State and Local Laws: Regulations For Open Controlled Burning

State and local laws pertaining to prescribed burning are in the category of regulations generally termed *"open controlled burning."* Because nationally, there is a great diversity of open burning laws, it would be impractical to catalog all of the applicable regulations. Instead, this Guide emphasizes the general nature of these rules and where to find the critical information needed by managers for specific smoke management decisionmaking.

A typical definition of *"open controlled burning"* is: Any fire from which the products of combustion are emitted into the atmosphere without passing through a stack or chimney. This definition incorporates aspects of prescribed, open, and controlled burning and could include activities such as sanitation burning and naturally ignited prescribed fire.

Regulatory Objectives

The two primary thrusts behind open burning regulations are fire safety and air quality control. The main goal of fire safety is to prevent damage to agriculture, rangeland, forestland, and private property during and after wildfires. The main goal of air quality control is to prevent violations of State and national ambient air quality standards and to reduce the number of nuisance complaints resulting from open burning. Nuisance complaints cannot be discounted, since they often have a more serious effect on curtailing prescribed fire programs than actual violation of existing standards. Safety and air quality objectives do not always complement one another, and conflicts often arise between the agencies that enforce them.

Jurisdiction

Several agencies enforce rules for open controlled burning. These agencies do not have exclusive authority; thus, several combinations of agencies may have jurisdiction over open burning activities. It is advisable to become familiar with all of the possible regulatory "mixtures" in the planning phase of smoke management. Usually a call to the State Forester or Pollution Control Authority will provide this information. Federal, State, city, county agencies, and fire control and air quality management districts may be involved. A list of contact people and telephone numbers for each of the various agencies involved should be maintained.

Determining Specific Requirements, Restrictions, and Exemptions

Once you have determined the regulatory authorities involved in an area, obtain a copy of their respective rules and identify a contact person within the authority from whom additional information can be exchanged. **Good communication is important!**

Open controlled burning regulations usually have the following components:

1. Declaration of intent.

2. Legislative authority.

3. Definition.

4. Prohibitions and limitations.

5. Open burning allowed.

6. Permitting or authorization requirements.

7. Exemptions.

Examples of the rules include setback or buffer distances from roadways and property lines, duration of burning authorization, weather and stagnation considerations, air quality alerts and episodes, permit fees, and fuel moisture limits.

Penalties for Violations and Potential for Liability

Prescribed Fire Managers are subject to numerous penalties for violations of open burning rules. These penalties should not be taken *lightly*. They can range from administrative warnings without fines to criminal cases with mandatory fines and jail sentences. Some authorities have arrest powers, but most use administrative actions to enforce their rules. More severe infractions merit civil, injunctive, or criminal actions. Fines can be as low as $25 for misdemeanors or as high as over $25,000 per day per offense for criminal violations. In addition to fines levied through criminal actions, prescribed fire managers can also be subjected to civil suits, which can run into millions of dollars.

State and Local Smoke Management/Controlled Burn Programs

State and local laws, rules, and regulations pertaining to open burning (which includes prescribed burning) vary considerably from State to State because they are affected by combinations of factors such as population centers, ventilation factors, temperature variations, topographical features, and resident vegetation and agricultural practices. Consequently, smoke management and prescribed fire programs also vary considerably.

Although many States do not have laws that deal specifically with the use of prescribed fire for range improvement and rehabilitation, most timber-producing States have laws which recognize the use of fire for timber slash burning, hazard reduction, hardwood control, disease control, wildlife habitat improvement, and site preparation for reforestation.

Some authorities have developed smoke management programs to deal with environmental and cost benefits of using prescribed fire as a management tool and the adverse impacts on air quality. Several areas with high population centers have intensive smoke management programs to protect sensitive populated areas from prescribed burning emissions. These smoke management programs deal with the weather conditions necessary to assure smoke dispersal and avoidance of smoke-sensitive areas (for example, population centers and national parks and recreational areas during periods of greatest use).

Smoke management plans typically consider four key factors: amount of material to be consumed in tons per acre, distance from smoke-sensitive areas, topography (especially elevation), and predominant weather conditions, including atmospheric stability, mixing height, and wind speed and direction. These key factors are used to meet the primary goal of a smoke management program, which is to minimize or prevent smoke accumulation within an area where prescribed fire is necessary.

States with strong smoke management programs actively seek the participation of Federal and local agencies, forest industries, and private landowners. In these more sophisticated smoke management programs, annual burn planning plays an extremely important role in the smoke management program.

Prescribed Fire Managers who coordinate with the State authorities and fully identify their plans for burning before the burning season are most likely to be able to conduct their burns. Such preliminary steps may be extremely important when burn prescriptions and predominant climate conditions create a limited opportunity to conduct burns.

Advanced smoke management programs work as follows:

1. Major open burners agree with States to abide by smoke management regulations through a mutually developed Memorandum of Understanding.

2. Signatories of the agreement obtain smoke management permits on an annual basis or by the unit.

3. A data base consisting of location, unit size, and estimate of tons to be consumed is developed for scheduling burns.

4. Each day during the burning season, a forecast of meteorological conditions for the airsheds is evaluated along with the proposed amount of burning to be accomplished in order to ascertain whether burning

restrictions should be imposed to keep smoke accumulation from reaching objectionable proportions.

5. In mountain-valley topography, smoke dispersion or atmospheric ventilation conditions often vary significantly with elevation. Burning restrictions are most frequent at lower elevations that are within a couple of thousand feet of major valley floors than at higher elevations.

6. Real-time information about restrictions on burning is provided to participants in the program. Smoke management restrictions are relayed before close of business the day before the burn so that firm plans can be made. This information is essential for cost-efficient use of burn crews.

7. The burning program is monitored, evaluated, and revised as appropriate to maintain good air quality.

Prescribed Fire Managers have a personal and legal responsibility to assure the success of smoke management programs. They must voluntarily curtail burning if their portion of an airshed is becoming overloaded with smoke or local weather factors are likely to create smoke problems, even though no burning restrictions have been issued.

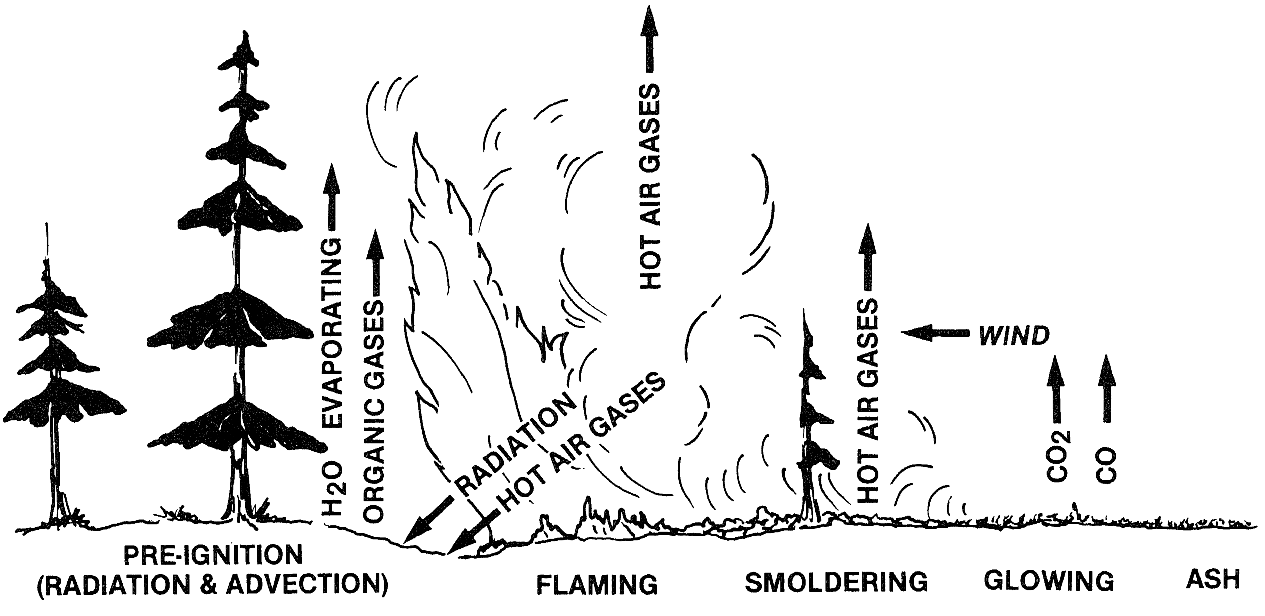
Chapter II. Smoke Production Characteristics and Effects

Ragnar "Bill" Johansen, John Deeming, Mike Long, Darold Ward

This chapter discusses the combustion process, the effect of fuel properties on smoke production, the characteristics of emissions, and the health hazards of smoke.

The Combustion Process

Most observers of forest fires distinguish between flaming and smoldering combustion. Flaming combustion is characterized by the movement of a visible flame through the fuel; smoldering combustion is a much more general and loosely defined term associated with the "die-down" of a fire after the flame front has passed. The burning process, however, is more complicated than this. It is more logical to consider it in four phases; preignition, flaming, smoldering, and glowing. The Prescribed Fire Manager and Burn Boss should understand this process to appreciate how the various smoke components are produced. These phases are illustrated in Fig. 1.



STAGES OF COMBUSTION

Preignition Phase (Distillation and Pyrolysis Predomination)

In this phase, fuel elements ahead of the fire are heated; this causes water vapor to move to the surface and escape. As the fuel dries and its internal temperatures rise, certain components of the wood decompose, releasing a stream of combustible organic gases and vapors. This process is called pyrolysis. Because these gases and vapors are very hot, they ignite when mixed with oxygen. This brings the process to its second phase, flaming combustion.

Flaming Phase (Rapid Oxidation of Gases Predominating)

At the beginning of this phase, the fuel temperature rises rapidly. Pyrolysis accelerates and is accompanied by rapid oxidation (flaming) of the combustible gases, which are now increasing in greater and greater quantities. The products of flaming combustion are predominatly carbon dioxide ($CO2$) and water vapor. This water vapor is not the result of fuel dehydration (preignition phase), but rather a product of the combustion reaction. Temperatures in this phase range between 600 and 2500 degrees Fahrenheit. Some of the pyrolyzed substances cool and condense without passing through the flame zone; others pass through the flames but are only partially oxidized, producing a great variety of emissions. Large-molecule organic compounds are synthesized here. Many organic compounds of low molecular weight remain as gases and move down wind; some compounds with higher molecular weights cool and condense into tar droplets and solid soot particles as they move away from the fire. These particles make up the visible smoke component with which we are primarily concerned. The more inefficient the burning, the more soot and tar produced.

Smoldering Phase (Slow, Flameless Combustion Predominating)

In this phase, the overall reaction rate of the fire has diminished to a point at which the concentration of combustible gases above the fuel is too low to support a persistent flame envelope. Consequently, the temperature drops and the gases condense. The resulting condensates appear as visible smoke as they escape into the atmosphere. Emissions from a smoldering fire are at least twice that for flaming fire. The heat release rate of a smoldering fire is seldom sufficient to sustain a convective column because the smoke stays near the ground and persists in relatively high concentrations, thereby compounding the impact of the fire on air quality. The smoke evolved during this phase is virtually soot-free, consisting mostly of tar droplets less than a micrometer in size. Near the end of the smoldering phase the evolution of pyrolysis products ceases, leaving the fuel as a black char. The final phase of combustion then takes place.

Glowing Phase (Solid Oxidation Predominating)

In the glowing combustion phase, all the volatile material in the fuel has been driven off. Oxygen in the air can now reach the fuel; the surface of the charcoal begins to burn with a characteristic yellow glow. There is no visible smoke. Carbon monoxide and carbon dioxide are the principal products of glowing combustion. This phase continues until the temperature drops or until only noncombustible, gray ash remains.

It is important to recognize that combustion in forest fires, even in the most favorable circumstances, is not a chemically efficient process. First, moisture contained in the fuel absorbs some of the heat energy, thereby reducing the combustion temperature. Second, considerable heat is subsequently lost to the soil and surrounding air. Third, fresh air movement in and around the fire cools the combustion zone. Also, the oxygen required for optimal combustion is sometimes insufficient, resulting in more visible smoke.

Fuel Moisture

The amount of moisture in fuels greatly affects the ease of ignition and the efficiency with which live and dead vegetation burn. By affecting flame temperature, hence combustion efficiency, moisture in the fuel affects the amounts and character of emissions. The *"cleanest"* fire is the most efficient fire because, by definition, its combustion is the most complete. On the other hand, though the emissions per unit of fuel burned will be greater at higher fuel moistures, the total emission production from a burn may be less if some fraction of the fuel (typically, the larger "round" fuels and the duff) does not totally burn.

Fuel Properties As They Affect Smoke Production

The total volume of smoke produced from a prescribed fire depends primarily upon the amount of fuel consumed. Smoke production can last from less than an hour to several weeks, depending on the method of ignition and nature of the fuel bed. The manner in which combustion and smoke production take place depends primarily on fuel moisture and such physical fuel properties as particle size, particle arrangement, and fuel weight per unit area.

Particle Size and Arrangements

With a given fuel moisture, the time necessary to ignite and consume an individual fuel particle depends upon the smallest dimension of the particle. A measure frequently used to depict particle size is the ratio of a particle's surface area to its volume—the greater the ratio the smaller the particle. Size is only part of the information needed when the particle is part of a fuel bed. The arrangement of the particles is also important. Up to a point, the greater the space between particles, the faster the particle will burn. A measure of fuel bed porosity is called the packing ratio, or that fraction of the fuel array volume occupied by fuel. Fuel beds made up of small particles, like juniper or spruce needles, will burn more slowly than beds composed of longer needles because the shorter needles pack more tightly, increasing their packing ratio and decreasing combustion efficiency. The basic premise applies: the more fuel available to burn, the greater the total smoke production. How the fuel is burned (i.e., ignition techniques) will affect smoke production and is discussed in Chapter III.

Fuel Loading

When using prescribed fire on areas with light fuel loadings under four tons per acre (such as grasslands or frequently burned pine stands) total smoke production is low because smoldering combustion is minimal in these types. Rate of smoke production will increase as rate of fire spread increases.

The heaviest fuel loadings a prescribed fire manager encounters are normally in piled logging debris. This type of burning can have the most adverse impact on air quality.

Fuel Continuity

Fuel continuity (both horizontal and vertical) affects smoke production because it affects the amount of fuel consumed. Most significantly, sustained ignitions will not occur when the spacing between fuel particles is too large.

Chemical and Physical Characteristics of Emissions

Knowledge about the products of combustion of forest fuels is emerging. Fuel carbon is converted into combustion products, many of which have not been completely oxidized. Hence, products from the combustion of forest fuels produce mostly carbon-containing compounds, the most important pollutants being particulate matter and carbon monoxide (CO). Other compounds, such as oxides of nitrogen (NO_x) and sulfur (SO_x), are present only in negligible amounts. Many of the compounds have high boiling points and tend to condense into droplets, forming clouds of smoke.

Gaseous Emissions

Two products of complete combustion, carbon dioxide (CO_2) and water, make up over 90% of the total emissions from wildland fires. Under ideal conditions complete combustion of one ton of forest fuels requires 3.5 tons of air and yields 1.84 tons of CO_2 and 0.54 tons of water. Under wildland conditions, however, inefficient combustion produces different yields.

As combustion efficiency decreases, less carbon is converted to CO_2 and more carbon is available to form other carbonaceous combustion products. Carbon dioxide is not considered a pollutant, but carbon monoxide, hydrocarbons (HC), nitrogen oxides, and sulphur oxides (SO_x) are.

Carbon Monoxide—Carbon monoxide (CO) is the most abundant air pollutant caused by prescribed fires. Its negative effect on human health depends on duration of exposure, CO concentration, and level of physical activity during exposure. Generally, dilution occurs rapidly enough to reduce the health hazards.

Hydrocarbons—Hydrocarbons (HC) are an extremely diverse class of compounds containing hydrogen, carbon and sometimes oxygen. Usually, the classes of hydrocarbon compounds are identified according to number of carbon atoms per molecule. Emission inventories often lump all gaseous hydrocarbons together, although the majority of HC pollutants may have no harmful effects.

Nitrogen Oxides—In prescribed fires, small amounts of nitrogen oxides (NOx) are produced, primarily from oxidation of the nitrogen contained in the fuel. Thus, the highest emissions of NOx occur from fuels burning with a high nitrogen content. Most forest fuels contain less than 1% nitrogen. Of that about 20% is converted to nitrogen oxide when burned.

Sulfur Oxides—Sulfur Oxide (SO_x) compounds are produced in negligible quantities because of the low elemental sulfur content of the forest fuel. Sulfur is lost from the site during burning, as is nitrogen.

Hydrocarbons, nitrogen oxides, and sulfur oxides have not been identified as a problem in prescribed burning and, therefore, are not included in smoke management strategies and plans.

Particulate Matter

Particulate matter emissions limit visibility, absorb harmful gases, and aggravate respiratory conditions in susceptible individuals. Over 90% of the mass of particulate matter produced by prescribed fires is inhalable and respirable. Respirable suspended particulate matter is that portion of the total particulate matter that, because of its small size, has an especially long residence time in the atmosphere and penetrates deeply into the lungs. Small smoke particles also scatter visible light efficiently and thus reduce visibility.

Emission Factors and Emission Rates

Because most of the adverse impacts from prescribed fire are caused by particulate matter in the smoke under adverse meteorological conditions, fire management personnel must know how much smoke they are producing. The answer can be derived via two numerical expressions, emission factor and emission rate.

Emission Factors.

An emission factor for particulate matter (EFp) is defined as the mass of particulate matter produced per unit mass of fuel consumed, i.e., lbs/ton in the English system or g/kg as the metric equivalent. Emission factors reported in the literature for forest fuels range from four to 180 lbs/ton, depending on fuel type and arrangement and the manner of combustion. In general, fuels consumed by flaming combustion produce much less particulate matter than fuels consumed by smoldering combustion. Suggested EFp values for generalized fuels are listed in Table 1 (See page 9). These values can be used as a guide to develop regional expressions of the most common fuel and fire types. They can also be used by local air quality agencies that need emission inventory information.

While particulate matter is the focus of our attention, the reader should be aware that emission factors are also available for other products of combustion such as the invisible gases, and they too vary considerably depending on the stage of combustion. Emission factors of carbon monoxide can exceed 500 lbs/ton under the worst case conditions during smoldering and glowing combustion. In contrast, the emission factors of the oxides of nitrogen and sulfur are greatest during high temperature, high intensity fires. However, the amounts produced are very small and do not have to be taken into account for wildland smoke management purposes.

Emission factors (EFp), in addition to being used as a variable in the calculation of local and regional emissions inventories, are also used directly in the calculation of an emission-rate expression for planning individual prescribed-burn strategy based on downwind concentrations of particulate matter.

Emission Rates

Emission rate is defined as the amount of smoke produced per unit of time (lb./min). Down wind concentrations of particulate matter in smoke are related directly to the emission rate at the fire source; the emission rate, in turn, is affected by the amount of fuel being burned, the rate at which it burns, and the emission factor of the fuel.

The amount of fuel actually consumed by a fire is called available fuel, and this fuel may be consumed by flaming or smoldering combustion. The unit of measure is usually in tons per acre. The land manager can make better estimates of emission rates from a prescribed burn if the amount of fuel consumption in each of the two types of combustion is known. Available fuel can be estimated before ignition and is usually less than total fuel loading. The rate at which fuel is consumed can be expressed as area burned per unit of time, that is acres per minute. The combustion rate parameter can be calculated whether line-type ignition is used for backing or heading fires or area-type ignition is used in natural fuels or in activity fuels.

Once estimates of the available fuel (tons/acre), the combustion rate (acres/minute), and the emission factor (lb/ton) are made, the emission rate can be calculated by the equation:

Emission Rate = Available Fuel x Burning Rate x Emission Factor

Emission rate is expressed in pounds per minute. The emission rate is used to drive models that predict concentrations of particulate matter. These models are used to assess the impact of smoke on visibility in sensitive areas such as cities, highways, and airports.

Table 1
Emission Factors For Particulate Matter as a Function of Fire Behavior[1]

General Fuel Type	Fire Behavior	Particulate Emission Factor
		Lbs/Ton[2]
Grass	Flaming dominates	15
Understory Vegetation and Litter	Flaming w/light smoldering[3]	25
	Flaming w/moderate smoldering[4]	50
	Flaming w/moderate smoldering[5]	75
Broadcast Slash	Flaming dominates	20
	Flaming w/smoldering component	40
Piled and Windrowed Slash	Flaming dominates[6]	25
	Flaming w/moderate smoldering	50
	Flaming w/heavy smoldering[7]	75
Brush Fuels	Flaming dominates	25
	Flaming w/moderate smoldering	50
All Fuels	Burning where smoldering dominates	150

[1] These emission factors are generalized estimates based on research data, combustion fundamentals and scientific judgment. They should be modified as needed in regional supplements to this guide in accordance with the latest information on fuels, firing technique, smoke particle size, etc. Further consultation can be obtained on western fuel types by calling or writing Darold E. Ward, Pacific Northwest Forest Range Experiment Station and Charles K. McMahon at the Southern Forest Fire Laboratory on eastern fuel types.

[2] Lbs/ton of fuel burned. 1.0 lb/ton = 0.5 g/kg (dry weight basis).

[3] i.e., backing fires or heading fires in light fuels without duff involvement.

[4] i.e., heading fires in litter fuels with heavy loading.

[5] i.e., fires in litter fuels with substantial duff consumption.

[6] i.e., soil free and very dry.

[7] i.e., heavy mineral soil component and/or high fuel moisture.

Residual Smoke

Residual smoke is defined as the smoke produced from smoldering combustion and not contained in a convection column. During the active combustion stage of almost all prescribed burns, smoldering combustion takes place near flaming fuels. Much of the smoke from the smoldering fuel is entrained into the convection column induced by the flames and carried aloft. When flaming ceases, the convection column dissipates and all subsequent smoke produced from smoldering combustion remains near the ground as residual smoke.

Smoldering combustion frequently causes a sudden visibility problem immediately down wind of a burn area when the convection column dissipates. The lack of vertical movement concentrates the smoke near the ground. If residual smoke production is brief following the completion of flaming combustion, the horizontal and vertical dispersion from air movement may still be adequate to prevent down wind problems.

Special problems arise from a prescribed fire if residual smoke persists into the night or into subsequent burning periods. In relatively flat terrain, wind usually is minimal at night, causing smoke density to build up in the vicinity of the burn area. Any nearby drainages usually further concentrates the smoke. In addition, the particulate matter can serve as nuclei for fog formation if the relative humidity approaches the water saturation point. In complex terrain the residual smoke can flow down drainages at night, causing visibility and other problems if the drainages contain sensitive areas.

Residual smoke that persists for several days poses additional problems because the manager cannot make reliable predictions of the wind speed and direction much beyond the day of the burn. The path long-term residual smoke will follow, therefore cannot be reliably predicted. The best burning plans should contain provisions to minimize residual smoke production. Residual smoke causes more road accidents than any other type of smoke.

Health Hazards of Smoke

Breysse, 1984, discusses health hazards associated with smoke. The following information is based on his article.

Inhalation of smoke from whatever source can cause acute or chronic damage to health. The acute, or immediate, symptoms are caused by exposure to high concentrations of smoke over short periods. Manifestations range from irritation of the eye and respiratory tract to impaired judgment, semiconsciousness, unconsciousness, and even death.

More insidious are repeated exposures to relatively low concentrations. These may result in respiratory allergies, bronchitis, emphysema, and cancer. Chronic health hazards are by far the most significant, because 15 or more years usually pass before the victim is disabled.

Hazards vary with the kinds of smoke inhaled. Smoke is a complex mixture whose components depend in part on the type of fuel, its moisture content, additives in the fuel (for example, pesticides sprayed on trees or foliage), and, of course, the temperature of combustion. Burning forest fuels discharge hundreds if not thousands of chemical compounds into the atmosphere—including carbon monoxide, total suspended particulates, hydrocarbons, nitrogen oxides, and water vapor.

Also released by burning vegetation are complex organic materials which are absorbed in, or on, condensed smoke particles. Penetration of these particles into the lung increases the chemicals' toxicity. Researchers consider particles with diameters of less than 10 um to be inhalable. Researchers also consider particles with diameters less than 2.5 um to be respirable. Over 90 percent of particulate emissions from forest fires are 10 um or less in diameter. The difference between the mass of particles produced that are less than 2.5 um in diameter to the total mass of particulate matter increases proportionally to fire intensity.

In addition, nitrogen oxides and hydrocarbons produced by the fire react together in the presence of sunlight to produce ozone and organic oxidants. Both of these are potent irritants.

Although periodic exposure to high concentrations of forest fire smoke for long periods can be dangerous, recognition and evaluation of the hazards, adequate controls, employee training, and an annual physical examination can significantly minimize the deleterious effects.

The process involved in smoke production from the deliberate burning of forest fuels in the management of our nation's forest, and the resultant effects of the products of smoke on man have been described. But understanding these processes is only a step in the solution to the problem of smoke in our environment. The next step involves the deliberate effort on the part of forest managers to manipulate smoke production and flow so as to minimize the effects of our actions. Our smoke must be managed.

Chapter III. Smoke Management

Ed Mathews, Lee Lavdas, Larry Mahaffey, Tom Nichols, Dave Sandberg, and Mike Ziolko

This chapter introduces principles of smoke management strategies for prescribed fire and describes several techniques for reducing or altering emissions or otherwise preventing unacceptable pollution levels.

Smoke management practices include fuel management and fire prescriptions to reduce available fuel loadings or improve combustion efficiency, firing and mop up techniques to reduce emissions, scheduling to enhance convection or dispersion, scheduling to ensure plume trajectory moves away from sensitive areas, and coordinating burning locations for the best overall result. Smoke management practices vary in different parts of the country; therefore Prescribed Fire Managers should consult or develop regional or local guides for information about smoke management techniques specific to their areas.

Determining a Need For a Smoke Management Program

Anyone who uses prescribed fire should consider smoke management practices. This may be as simple as not igniting a fire when the surface wind at a burn site is blowing towards a highway. Smoke management may be as complex as prioritizing individual burns, monitoring fuel conditions, monitoring surface and upper air meteorological parameters, predicting down wind particulate and visibility impacts. In areas where smoke from prescribed fire has little potential for air quality impacts, smoke management considerations can be determined by individual burners. In areas where there is a problem it may be necessary to develop a smoke management agreement and plan which includes all users of prescribed fire and appropriate air regulatory agencies. To determine the level of sophistication needed for smoke management in a specific area, the following factors should be considered:

1. Does prescribed burning cause or contribute to violations of particulate standards? In general, the 24-hour standard has the most potential to be violated.

2. Does smoke from prescribed burning result in public health and safety problems such as on highways or airports? It is possible to cause significant safety problems even though particulate standards are not violated.

3. Are there any other areas which should be considered as smoke sensitive?

4. Does smoke from prescribed burning result in complaints from the public? It is possible to receive numerous complaints even though particulate standards are not exceeded?

5. Does the topography or meteorology cause poor smoke dispersion? Mountainous terrain and stagnant high pressure systems usually cause the most problems.

6. Is the amount of prescribed burning predicted to increase or decrease?

7. Are there limitations on the number of days available for prescribed burning because of fire hazard, stagnation problems, visitor or livestock use, etc.?

8. Does prescribed burning impact any areas where visibility is an important value?

Each smoke management program will vary because of differences in amounts of fuel burned, fuel types, topography, meteorology, and presence of smoke sensitive areas.

Control Strategies

Avoidance, dilution, and reduction of emissions are ways to manage smoke from prescribed fires. **Avoidance** is a strategy of considering meteorological conditions when scheduling fires in order to avoid incursions of prescribed burning smoke into smoke sensitive areas; for example, a populated area where any noticeable impact is objectionable. **Dilution** involves controlling the rate of emissions or scheduling for dispersion to assure a tolerable concentration of smoke in designated areas. **Emission-reduction** techniques minimize the smoke output per unit area treated and decrease the contribution to regional haze as well as intrusions into designated areas. One way to reduce emissions is to treat fuels and prepare seedbeds using treatments other than fire, including the option of no treatment.

Avoidance

Pollution can often be prevented by scheduling prescribed fires during conditions that make intrusions of smoke into smoke-sensitive areas unlikely. This approach is particularly useful when few burns need to be scheduled.

The most obvious way to avoid pollution impacts is to burn when the wind is blowing away from all smoke-sensitive areas. Most fires have an active burning period and a residual period. Wind direction during both periods must be considered. At night, drainage winds can carry smoke toward smoke sensitive areas. Residual smoke is especially critical at night.

A layer of stable air, such as a temperature inversion, can isolate smoke originating above the stable layer from receptors below. In mountainous terrain, burning should occur when the stable air layer is below the elevation of the prescribed fire and other conditions are favorable. This is true even at night, except that a stable layer may not eliminate entrainment of smoke by drainage wind.

Dilution

Smoke concentration can be reduced by diluting smoke through a greater volume of air, either by scheduling during good dispersion conditions or burning at slower rates (burning smaller or narrower strips or smaller areas). Caution: Burning at slower rates may mean that burning continues into the late afternoon or evening, when atmospheric conditions become more stable.

The mixing-layer depth is the thickness of the layer of air into which the smoke is eventually diluted by atmospheric mixing. This depth depends on the stability of the lower atmosphere. Stability conditions favorable for burning are a weak or no-inversion condition at night and warm unstable air in the afternoon. A high-intensity fire may overcome some shallow low-level stable layers. The time of day at which ignition occurs is also an important consideration because mixing height and transport wind speed are likely to change during the day and night. Generally, a burn early in the day encounters improving ventilation rates; an evening burn encounters deteriorating ventilation rates.

Emission Reduction

Emission reduction can be an effective control strategy for attaining smoke management objectives. Effective firing techniques and proper scheduling can minimize the smoke output per unit area treated. For example, backing fires minimize the inefficient smoldering phase of a prescribed fire. Scheduling prescribed fires for periods when duff and larger fuels are too wet to burn will assist in reducing emissions. Removing large material also reduces emissions since less smoke will be put into the air and less residual smoke will be present.

Techniques to Minimize Smoke Production and Impacts

Prescribed burning, though necessary for accomplishing certain resource management objectives, can degrade air quality. The practice of prescribed burning carries with it an obligation to eliminate or minimize any adverse environmental effects, including those caused by smoke. The following guidelines will help reduce impacts.

Have clear objectives. Be sure you have clear resource management objectives which consider the impact of smoke on the total environment—both onsite and offsite.

Obtain and use weather forecasts. Weather information and fire-weather forecasts are available to all resource managers. Be sure to use them. To obtain forecast information, contact your local National Weather Service (NWS) office or your local Federal or State fire management agency. This weather information is needed to determine what will happen to the smoke, as well as to determine the behavior of the fire.

Do not burn when air stagnation advisories are in effect, during pollution episodes, or when temperature inversions exist. Under such conditions, smoke tends to stay near the ground and will not readily disperse. Many fire-weather forecasters include this information in their regular forecasts or will provide it if requested.

Comply with air pollution control and smoke management regulations. Know the regulations for your State and local area when developing the prescription. Procedures for compliance may require notification to air pollution control authorities having jurisdiction in your area prior to igniting a prescribed fire. If unsure, check with your local air quality or fire management agencies.

Burn when conditions are good for rapid dispersion. The atmosphere should be unstable so smoke will rise and dissipate; but not so unstable as to cause a control problem. Again, a fire weather forecaster can help.

Determine whether the direction and volume of smoke will affect public safety on highways and populated areas.

Use caution when near or upwind of smoke-sensitive areas. Burning should be done when transport wind will carry smoke away from heavily traveled roads, airports, and populated areas.

Notify the local fire-control office, smoke management monitoring unit, nearby residents, and adjacent landowners. This is common courtesy, as well as a requirement in most areas. All concerned will know the burn is not a wildfire, and you will get advance notice of any adverse public reaction.

Use test fires or helium-filled balloons to assess transport winds for smoke behavior. Set your test fire in the area proposed for burning, away from roads, or other "edge" effects.

Burn under favorable moisture conditions. The Prescribed Fire Manager can reduce smoke by selecting the correct combination of fuel moistures and burning only those fuels that must be removed to meet the burn objective. If the objective is to remove fine and intermediate fuels to reduce wildfire hazard, the burn should be accomplished when the relative humidity is low enough for fine and intermediate fuels to burn readily and larger fuels and duff are wet. If the objective is to expose the mineral soil, the burn should be conducted when the larger fuels and the duff are dry enough to burn with a minimum of smoldering.

Use backing fires when applicable. This is because backing fires, with their slow rate of spread and relatively long residence time, cause a higher fraction of the fuel to be consumed in the flaming stage of combustion rather than in the smoldering stage. Since total smoke production per unit of fuel burned is considerably less during flaming combustion, backing fires favor lower total smoke production.

Burn in small blocks when appropriate. The larger the area being burned, the more visibility is reduced down wind and the higher the concentration of particulates put into the air. It may be better, however, to burn all the area needed when weather conditions are ideal for rapid smoke dispersion.

Mop-up. Burn out and start mop-up as soon as possible to reduce impacts of residual smoke on visibility and health.

Expand your burning season. Fire managers should consider extending the burning season to times other than the "traditional" burning season. An extended burning season can benefit air quality because conditions may be more conducive to reduced smoke production and better lofting and smoke dispersion. Total impact on the air resource could thus be spread over a longer period, thereby reducing the possibility of a heavy smoke load during traditional burning seasons.

Be cautious when burning at night. Predicting smoke drift and visibility is more difficult at night. Winds may lessen or die out completely, and smoke will tend to stay near the ground. Although burning at night may help achieve other objectives, it may aggravate smoke management problems.

Have an emergency plan. Be prepared to control traffic on nearby roads if wind direction changes. Be prepared to construct control lines and stop a prescribed burn if it is not burning according to plan or if weather conditions change.

To minimize emissions, keep soil out of dozer piles and windrows by using rake-type blades. Dozer piles may produce fewer emissions than windrows due to more efficient combustion. Cover the tops of hand piles if you do not intend to burn them until surrounding fuels are wet or snow covered. Covered piles are drier, ignite more easily, are consumed more quickly, and produce less smoke than uncovered piles.

Weather Interactions

As weather patterns change, so does smoke behavior. General pressure patterns and fronts have pronounced effects on transport wind and stability characteristics of the atmosphere and affect how well the smoke will disperse.

Fronts

Frontal activity plays an important role in smoke behavior. Smoke movement and dispersion differ drastically with the type of front. The speed of an approaching front is an important consideration when executing burns. A slow moving front results in steadier wind speeds and gradually changing wind directions. A rapidly moving front has more sudden changes in wind speed and direction. By knowing how long a burn will last and how long a wind condition will exist, you can evaluate the likelihood of success in keeping smoke out of a sensitive area.

Cold Fronts—It is important to know the type of front affecting an area. Wind and stability characteristics associated with different types of fronts vary considerably. Cold fronts typically have rapid wind shifts and gusty winds. Behind a strong cold front, the air mass is generally unstable, which facilitates smoke dispersion and good visibility. Smoke impacts behind a strong cold front tend to be short, but high concentrations may occur locally. For some regions of the United States, it may be advantageous to burn just before passage of a cold front because smoke could be vented into a cloud layer and thus not create aesthetically unacceptable smoke layers over sensitive areas. Control problems may be associated with strong cold-fronts, however. Dispersion patterns are not nearly so good behind weak, slow moving cold fronts. The inherent stability associated with the cold surface air mass often traps smoke near the ground. In a strong cold front this effect is largely overcome by high surface wind speeds. In a weak cold front the lower wind speeds do not overcome this effect.

Warm Fronts—Burning associated with warm frontal activity can result in high smoke concentrations for long periods of time. Wind speeds are typically lighter and shifts in direction are more gradual compared to a cold front. This results in a given area being down wind of a burn for a longer period. Also, as a front approaches, upper stable layers descend, resulting in a lower mixing height and a smaller mixing volume for smoke. Normally, visibility decreases as rain and fog occur ahead of the front. Smoke, in the decreasing volume of air, will combine with the fog and rain to give extremely low visibility. Burning should be timed so that significant quantities of smoke are not present during the hours before frontal passage, when visibility could normally be expected to be reduced by rain or fog. Conditions can be expected to improve somewhat as the front passes, but overall dispersion would still be limited due to light wind speeds.

Stationary Fronts—The variable and changing wind conditions that characterize stationary fronts make forecasting smoke movement difficult. Light wind generally blows in opposite directions on either side of the front. The front meanders, resulting in variable transport winds with no sustained or predictable directions. Poor mixing and dispersion can be expected near the front with light winds, precipitation, and reduced visibility. Burning should be limited because smoke will intensify frontal characteristics and naturally occurring poor visibility.

Pressure Patterns

As discussed earlier, a key to managing smoke is evaluation of which way the wind will blow. Pressure patterns determine the wind fields and affect stability. This occurs because temperature affects pressure. As temperature changes, either diurnally, as a result of weather systems, or seasonally, so do pressure patterns, wind, and stability.

Coastal and mountainous areas are especially susceptible to diurnal changes in pressure and wind due to differential heating, which causes sea breezes and mountain-valley winds. These pressure changes completely reverse wind direction, which means that a burn starting out with smoke blowing away from a sensitive area may end up with smoke blowing toward the area.

Another important consideration is the type of pressure system that is affecting the burn area. A high-pressure system (or ridge) is one of stable air, light wind, and poor dispersion. Generally, burning under such conditions should be limited, as should burning under forecast conditions of a rapidly building high. When a high is rapidly building, one could expect rapid stabilization of the air mass and trapping of smoke at low levels.

A low-pressure system (or trough) represents a more unstable atmosphere. Wind fields are stronger with a low pressure system than under highs, which results in better dispersion. Smoke impacts tend to be much briefer, if they occur at all, than they would be under a high-pressure system.

The frequency of highs and lows varies considerably by seasons. Burning opportunities could be enhanced by taking advantage of known seasonal variations in stability and dispersion. Fire-weather forecasters, local meteorologists, and the National Climatic Center provide valuable assistance in supplying information for planning burning activity.

A user-oriented computer system allows Prescribed Fire Managers to quickly and easily analyze climatological data for the purpose of predicting the probable occurrence of desired conditions for prescribed fire. Four computer-based routines (RXWTHR, RXBURN, RXBUILD AND RXFIRES) make up the system. RXWTHR AND RXBURN programs are designed to use National Fire Weather Data Library climatological data. Information on the fire management planning aids is available through the U. S. Department of Agriculture, Intermountain Forest and Range Experiment Station, Forest Service.

Wind

The obvious first consideration in evaluating whether a burn will impact a sensitive area is to determine which direction the wind is blowing or will blow. Both the surface wind and wind aloft will affect behavior.

Surface Wind—Surface wind can result from general large-scale weather patterns or from local effects such as the sea breeze and mountain-valley flows mentioned previously. Local wind patterns are common in complex terrain or near water-land interfaces. They may extend for short distances or for distances up to 100 miles. The winds vary as to time of onset and decline in strength and depth, depending on aspect, time of day, time of year, and slope. Down slope or down valley winds can also affect the stability of the air mass by bringing cooler air to valley bottoms and thus forming inversions. Local winds can be reinforced by the general wind field or destroyed by the general wind depending on the strength and direction of each. For example, a strong general wind field blowing in the opposite direction of a local wind would negate the local wind. Information about local wind fields can probably be obtained from meteorologists familiar with the local weather or from meteorological publications.

Large-scale or general surface wind patterns are those associated with fronts, troughs, and ridges. The effects of these weather systems on wind fields are usually easily determined by reading weather forecasts. Planning and executing burns can be enhanced by taking advantage of the classic wind changes associated with the weather systems.

Understanding surface wind characteristics, either from local wind or general wind, is important to smoke management. Smoke from the smoldering stage of a burn will be caught in the surface wind. The Prescribed Fire Manager should plan this burn so the smoldering phase does not occur at the same time of the day as a predictable but unfavorable change in wind direction. To avoid sensitive areas, lengthy low-intensity burns may have to be accomplished during periods when no significant wind changes are expected. Local winds will transport smoke to various locations at different times of the day and night.

Another point to consider is that strong surface winds tend to bend plumes over, thereby not allowing maximum height development. In such cases, the smoke produced from the convective and nonconvective phases will be under the influence of surface wind patterns.

Upper Winds—Upper winds are also important in smoke management. The upper wind field is not as prone to local effects as is the surface wind. Sudden changes in wind speed or direction (wind shear) as a result of terrain influences, stability changes, or frontal boundaries can profoundly affect fire behavior and plume rise. Wind-shear layers can be as effective as stable layers in inhibiting or limiting plume rise.

Another concern with upper winds is that, although surface wind direction may be acceptable in keeping smoke from impacting a sensitive area, upper winds from a different direction may blow smoke over or through a sensitive area.

The smoke manager must fully understand the total wind pattern that is affecting the area during the burn as well as the wind that will be affecting the area around the burn during and after the burn. Initial success at keeping smoke away from sensitive areas will be overshadowed by a failure to recognize wind shifts which result in impacts on sensitive areas.

Dispersion

Dispersion refers to those processes within the atmosphere which mix and transport pollutants away from a source. The concentration of smoke experienced at down wind locations greatly depends upon weather conditions at the fire site and on the down wind smoke path.

Atmospheric dispersion mainly depends on three characteristics of the atmosphere: atmospheric stability, mixing height, and transport wind speed. Atmospheric stability is a measure of the tendency for vertical mixing to take place in the atmosphere. Mixing height is that height through which the mixing process is relatively complete. Transport wind speed is the average diluting wind speed within the smoke-laden layers of the atmosphere.

Stability

The effect of atmospheric stability on plume dispersion is not always fully appreciated or understood by prescribed burners. Stability affects the mixing of smoke during the convective phase as well as during the nonconvective phase of the burn.

Stable Atmosphere—During the main convective phase in a stable atmosphere, smoke will—at best—rise to some altitude and remain there. More likely, the smoke will start settling to the lowest levels of the atmosphere, and high smoke concentrations will result (Fig. 2). The smoke from the smoldering phase will remain near the surface and be moved around by the surface wind.

A poor time to burn is when a stable, high-pressure area is forming with an associated subsidence inversion. The subsiding air not only creates a more stable atmosphere but also one in which mixing volume decreases with time. It is often stated that supplying enough heat by burning can break through an inversion, thus eliminating the smoke as a problem. Only under special circumstances does this occur, however: 1) if the inversion is already being destroyed naturally; 2) if the burn is very close to the inversion; and 3) if the fire is extremely large and hot. The third circumstance is contrary to good smoke management practices because a hot fire burning over a large area is likely to have significant levels of nonconvective smoke which would not disperse well under stable conditions unless the fuels were flashy (fine) with little residual burning.

Stable conditions are readily apparent to the observant manager. Indicators are cloudless nights with light winds; hazy conditions and reduced visibility; clouds with a flattened or layered appearance; and light winds.

Unstable Atmosphere—An unstable atmosphere tends to have cumulus clouds with good vertical extent, good visibility, strong, gusty winds, and hot, clear days (without any low-level subsidence inversions) (Fig. 3). Unstable air masses tend to aid good mixing of smoke plumes with little, if any, long-term high volumes of smoke. The best overall mixing is not, however, necessarily associated with the most unstable atmosphere.

For most prescribed burning, a slightly unstable atmosphere tends to produce an optimum dispersion pattern, particularly when surface wind speeds are moderate.

See Figure 2 and Figure 3 on page 17.

Neutral Atmosphere—A neutral atmosphere is one in which vertical mixing and plume-rise are neither enhanced nor suppressed. The level at which a parcel of smoke reaches equilibrium with the surrounding air is the level at which it remains. Cloudy conditions with moderate wind speeds are indicators of neutral atmospheric conditions. Burning activity can generally be planned under neutral stability conditions as long as the wind direction is away from a sensitive area.

Relative Humidity

Other than its relationship to fine fuel moisture and subsequent fire behavior, the major impact of relative humidity is on visibility. As relative humidity increases, natural visibility may decrease due to increased water vapor in the air.

The significance of relative humidity to prescribed burning is that, as smoke particles are added to the atmosphere, they combine with the water vapor at these higher humidities to significantly reduce visibility. Smoke particles can also be the stimulus for fog or cloud formation, which reduces visibility. Reduced visibility can negatively affect airport operations and highways. To reduce the impact of smoke on visibility-sensitive areas, prescriptions should be prepared with the lowest feasible relative humidity consistent with fire control. Frontal passage, time of day, and elevation will affect relative humidity.

Mixing Height

Atmospheric mixing height is that height through which relatively vigorous mixing takes place. A mixing height exists only when the lower atmosphere is unstable or neutral. Above this height is a layer of stable air which acts to suppress vertical mixing. The result is as if a *"lid"* were placed upon the atmosphere, above which smoke penetrates very slowly. The higher this *"lid"*, the better the conditions for smoke management because a reasonably deep layer of vigorous mixing is needed to maintain low background concentrations in the lower atmosphere. Even if a prescribed fire emits low quantities of smoke, it may aggravate air quality problems when mixing height remains low.

During stable atmospheric regimes, there is no mixing height; that is, there is no height below which dispersion processes are rapid. Because high smoke concentrations are maintained for extended distances in such conditions, no burning should occur. Smoldering fires should be extinguished.

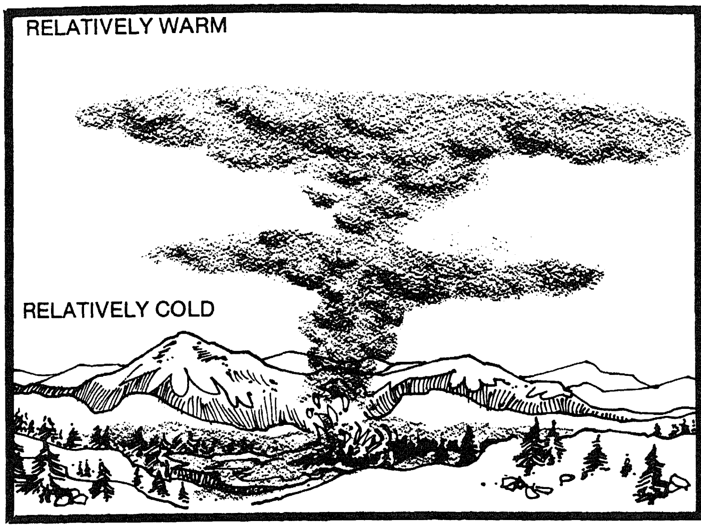
Visibility Protection

Visibility protection is an important goal of smoke management.

At high relative humidities, a small concentration of smoke can trigger fog formation. On roadways, high humidity combined with smoke has led to tragedy. Poor visibility of this nature is caused by condensation of atmospheric moisture on smoke particles, resulting in a greatly increased number of particles of the size range which block out light. This condensation process begins for certain types of airborne particles at relative humidities around 70 percent. As the humidity increases to nearly 100 percent, condensation is much more likely. For southern regions of the United States, highway visibility management has been addressed in the *"Southern Forestry Smoke Management Guidebook."* This publication cites a method that can be used to calculate visibility (in miles) based on total suspended particulate matter concentrations during dry weather.

Long-Duration Fires

Prescribed fires in wilderness and national parks can cause air quality problems that are not experienced elsewhere. For example, prescribed fires caused by



CLOUDS IN LAYERS,
NO VERTICAL MOTION

STRATUS TYPE CLOUDS

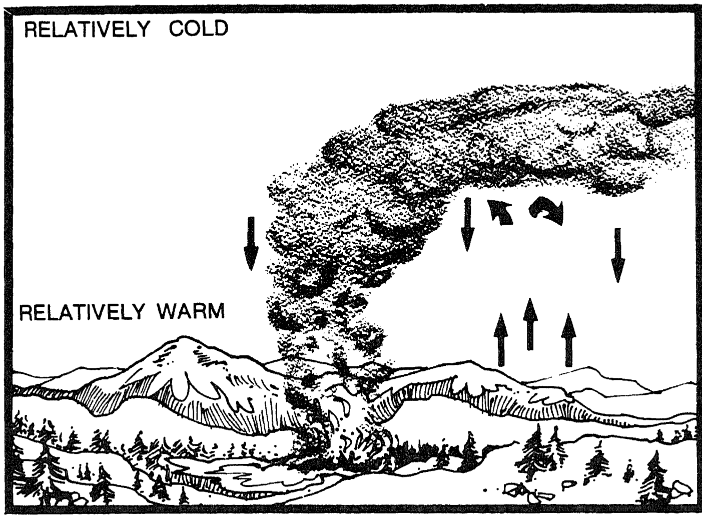
SMOKE COLUMN DRIFTS APART AFTER LIMITED RISE

POOR VISIBILITY IN LOWER LEVELS DUE TO ACCUMULATION OF HAZE AND SMOKE

FOG LAYERS

STEADY WINDS

Figure 2 Visible indicators of a stable atmosphere.



CLOUDS GROW VERTICALLY AND SMOKE RISES TO GREAT HEIGHTS

CUMULUS TYPE CLOUDS

UPWARD AND DOWNWARD CURRENTS
GUSTY WINDS

GOOD VISIBILITY

DUST WHIRLS

Figure 3 Visible indicators of an unstable atmosphere.

lightning, or even some caused by humans, may be allowed to burn for weeks or months to achieve certain management objectives. These long-duration fires typically burn under all types of meteorological conditions and can grow to fairly large sizes (1,000 to 15,000 acres). Thus, the potential exists for these fires to produce a large volume of smoke that eventually crosses wilderness and park boundaries. This smoke can affect smoke-sensitive areas, cause health-related problems to people with respiratory ailments, impair the ability to detect new fires, and saturate local airsheds to the extent that additional prescribed fires may not be ignited. Although it is difficult to predict future smoke episodes, the prescribed fire manager needs to:

1. Develop contingency plans to limit smoke production if the need arises (for example, contain a portion of the fire with a fire line to restrict further

2. Establish and maintain close communications with state and local air quality groups regarding the status of such fires.

3. Monitor smoke plumes as appropriate to provide some advance warning of deteriorating air quality conditions.

4. Inform the general public of the status of such fires, including smoke management contingencies, through the local press, radio, and television.

5. Consider suppressing new fires when necessary for smoke management reasons, even though these fires may otherwise be in prescription.

Costs and Benefits of Smoke Management

Managing prescribed fires to minimize the impact on air quality can increase the cost of burning projects. Smoke management costs vary by area and intensity of the program. Smoke-sensitive areas with comprehensive smoke management programs are experiencing additional costs.

Factors affecting costs of smoke management include:

1. Mop-up beyond the needs of controlling the fire.

2. Special ignition patterns and methods to develop, control, and monitor a smoke column.

3. False starts. Equipment and personnel are in place, but smoke advisory prohibits burning.

4. Reduced number of burning days. More equipment and personnel may be needed to burn more acres on a given burning day.

5. Additional fire control costs. Managers may have to burn on days when escape potential is higher in order to meet smoke management objectives.

6. Meteorological specialists and instruments may be needed to predict plume trajectory and mixing potential.

7. Cost for training, personnel coordinating, and administering smoke management activities to meet Federal, State, and local regulations.

Benefits resulting from Smoke Management include:

1. Reducing the risk of accidents on highways and other sensitive areas.

2. Reducing the risk of liability suits.

3. Reducing the risk of a "regulatory approach" replacing voluntary approaches on a State and local level.

4. Improved public health and welfare.

5. Fewer intrusions in smoke sensitive areas.

6. Improved visibility.

7. Reduced public complaints.

Although an effective smoke management program costs money, it may be the only way that prescribed fire programs can be conducted and contained in smoke-sensitive areas. Smoke management must be considered as one of the costs of doing business.

Chapter III, Smoke Management, introduces and describes several smoke management strategies that can aid resource managers in managing smoke from prescribed fires. Techniques have been included which may assist prescribed burners in minimizing emissions and related impacts from smoke. Sections on weather interactions and dispersion principles highlight the often highly interrelated effects weather factors have on smoke behavior and movement. Readers are encouraged to consult regional guides for specific information regarding smoke management techniques and practices in your area.

Chapter IV.

Smoke Monitoring and Evaluation

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Although there are no regulations that require prescribed fire smoke to be monitored, there are stewardship principles and ethical reasons that sometimes make monitoring a compelling factor in good smoke management policy. With proper planning and execution, the risk of creating a smoke problem with prescribed burns can be minimized. As a first step, managers must develop and maintain an awareness of air quality monitoring techniques. This awareness will facilitate an evaluation of program effectiveness and effective communication with local air quality (AQ) personnel. Familiarity with air quality monitoring does not require having an elaborate array of monitoring instruments or hiring a monitoring contractor to evaluate burns. We do recommend the following:

1. Understand air monitoring concepts and instrumentation.

2. Develop a smoke management/monitoring component in conjunction with your prescribed burning plan.

3. Develop a systematic and objective method to evaluate the effectiveness of your smoke management efforts.

To help you begin the awareness process, this chapter briefly reviews why and how air is monitored by AQ personnel and what monitoring technology you may need to be aware of in your prescribed burning program development and evaluation. For items 2 and 3 above, no one approach will suffice for all regions, agencies, and burning programs. Regional supplements to this Guide should provide specific procedures to assist you with your operations; however, we will describe monitoring efforts being explored in the Southeast and Pacific Northwest as examples of current technology.

While no readily available operational smoke monitoring techniques accurately predict the effect of a given prescribed burn on air quality, understanding principles of air monitoring can result in better smoke management decisions.

Monitoring Role—Air Quality Regulatory Agencies and Land Managers

In its broadest sense, the term "air quality monitoring" is usually defined as any systematic, planned means of determining the quality of the ambient air over a defined time interval in a geographic area. Monitoring programs can be federally sponsored national networks or they can be localized efforts sponsored by a city or county air resource board. It is important to know what ambient air quality monitoring networks are in place in the vicinity of prescribed burns.

It is the responsibility of state/local Air Quality Regulatory agencies to determine the impact of prescribed burning on areas which exceed air quality standards. This information is used to develop control programs. In addition, the regulatory agencies need to determine if the burning causes Air Quality standard violations. Land managers use monitoring information to evaluate effectiveness of Smoke Management programs, monitor impacts that may have public safety consequences and respond to public concerns. The land manager and the Air Quality Agency are jointly responsible for developing visibility monitoring programs for Class I areas.

Ambient Air Quality Monitoring for Air Pollution Standards

From a regulatory perspective, air quality is judged against legally adopted national or state ambient standards or both. In most cases, a time-averaging term is specified, such as hourly, 8-hour or an annual mean. It is fairly well accepted that in prescribed burning, particulate matter (visible smoke) is the pollutant with the highest potential for violating standards. Specifically, the Secondary National Ambient Air Quality Standard (24-hour standard) for total suspended particulate (TSP) is an area of risk for prescribed burns. The current (1984-85) 24-hour TSP standard is 150 ug/m3 for particles smaller than 50 um. EPA is considering a new 24-hour standard for particles less than 10 um in diameter (PM-10). States are permitted to adopt more stringent standards than those proposed and adopted by EPA.

In an area subject to inversions, it is vital to know the details of the episode-control plan. Know the legal authority, monitoring, and surveillance systems.

Prescribed Fire Emissions Inventory

Prescribed fire emission inventory and source monitoring for prescribed burning is a difficult and expensive process, and every agency and prescribed burning program cannot be expected to have the resources to develop their own source monitoring program. It is essential, however, to develop a data base that answers the questions—where, when, and how much fuel is burned.

Overview of Smoke Monitoring Methods in Use by Air Quality

Regulatory Agencies

Particulate matter is a difficult substance to monitor; however, a number of monitoring instruments and methods have been developed and are being used today. The following sections describe a few of the air quality surveillance methods and monitors are available and in use by AQ agencies for visibility and smoke monitoring.

High-Volume (Hi-Vol) Samplers—The High-Volume Sampler is the most widely used particulate matter monitor and is the standard reference method used by EPA and states to monitor compliance with the National Ambient Air Quality Standard for TSP. The Hi-vol is a large filter connected to a vacuum type motor/blower and a timer. Hi-vols are used as a source monitoring device and have little utility in operational prescribed fire programs because a hi-vol is an "ambient" monitor and presumes it is sampling a well-mixed air sample representative of a very large area surrounding the sample site. A hi-vol near a single source will be biased by that source and monitoring results will not be representative of the designated area.

When EPA began deliberation of adopting a new particulate standard, new monitors were rapidly developed. These are known as dichotomous or size selective inlet samplers. In general, they operate like hi-vols except that the sampler inlets are designed to screen out particles larger than 10 um. As indicated in Chapter II, most prescribed fire smoke particles are smaller than 10 um.

Real-Time Particulate Monitors—Air pollution agencies are required to continuously monitor particulate levels during air pollution episodes to protect the public health. These methods include beta-gauge monitors, tape samplers and nephelometers. Beta-gauge monitors have largely replaced older tape sampler systems since they are much more accurate. These instruments measure hourly particulate concentrations by detecting the reduction of beta rays as they pass through the sample. Nephelometers measure the amount of light scattering associated with fone particles in the atmosphere that reduce visibility. They can be used as an indication of TSP concentrations if a nephelometer/hi-vol correlation can be established.

Visibility Monitors—The teleradiometer is an instrument that measures light intensity or brightness over a given distance or path length, which may be 20 or 30 miles or more. Nephelometers are also used as visibility monitors.

Although teleradiometers and nephelometers are used primarily by air resource management agencies, land management agencies are also beginning to use them. Land managers have generally used this equipment in research studies and not as an operational tool but there is a trend in using visibility data to assess the impact of air pollution sources, such as new industrial facilities, on the visibility resource of Class I areas.

Overview of Smoke Monitoring Methods in Use by Land Managers

Visual Estimates—This is the most common method in use. Some agencies use a test fire coupled with visual observations to ensure that the smoke plume does not affect a smoke-sensitive area. Although visual methods are subjective and limited, they are still very useful.

Photo Documentation—Photo points are established adjacent to project locations. A permanent record of plume height, color, and direction is obtained. This method has proven valuable in documenting responses to public complaints.

Aircraft Plume Tracking—Aircraft tracking is a relatively expensive method presently in limited use by researchers and some regulatory agencies. In Oregon, aircraft are being used to identify violations of air quality/smoke management regulations and to verify forecasts.

Balloons—Fire managers have reported using small helium-filled balloons to determine midlevel wind direction to ensure that their smoke does not impact any smoke-sensitive areas.

Smoke Dispersion Prediction Systems

Single Fires, Flat Terrain—Under these conditions smoke dispersion can be predicted using techniques that are described in the Southern Forestry Smoke Management Guidebook. The outputs of this system allow the manager to decide whether concentrations of TSP are above or below selected standards.

Inputs include some information about the meteorological conditions (wind speed, direction, and cloud cover) at the burn site. This information is used to calculate potential smoke concentration down wind. The calculations are based on assumptions that the measured wind characterizes the path followed by the smoke. This assumption is rarely correct when the fire is located in or near mountain terrain or coastal locations.

Smoke Screening Process—This is a computerized data base that includes weather forecasts as well as locations of smoke-sensitive areas. Users input information such as location and magnitude of planned fires. They receive information about the potential of the fire or fires to cause visual impacts on any smoke-sensitive areas. The automated system uses the Weather Service as well as local meteorological data and diffusion models which predict down-wind concentrations. The system is in early stages of operation in the Forest Service, Pacific Northwest Region. More details are available from the Pacific Northwest Region Aviation and Fire Management Staff or the Southern Forest Fire Laboratory, Dry Branch, Georgia.

Topographic Air Pollution Analysis System (TAPAS)—TAPAS is a system of models for predicting the dispersion of air pollution over flat and mountainous terrain. Variables of topography, wind speed, and direction are used to model plume direction and dispersion to predict ground level concentrations of smoke. Because the system does not include any emission models, the manager will require some knowledge of relationships between fire and emissions. TAPAS currently operates on the Colorado State University computer system. Documentation and more information is available from the Rocky Mountain Experiment Station, Fort Collins, Colorado.

We started this chapter by pointing out that there was not a regulatory requirement for you to monitor your smoke. We then go on to describe both simple and complex monitoring methods that are in use or under development. This may seem a bit foolish at first. Why monitor your smoke when you really don't have to?

The fundamental basis for smoke management and monitoring is rooted in the principles of resource management. In fact, smoke management may be better labeled as 'air resource management.' After all, we readily accept our stewardship responsibility over the land and water we manage. Why not over the air?

In the final analysis, it boils down to this: *If you don't take a rational, voluntary approach to smoke management, a not-so-rational, mandatory approach may be just around the corner!*

Smoke Management Glossary

This glossary is a compendium of terms used in the operation of Smoke Management Programs. Terms included are those used in the fields of meteorology, air pollution and forestry.

Aerosol - A colloidal system in which the dispersed phase is composed of either solid or liquid particles in which the dispersion medium is some gas, usually air. See Particulate Matter

Air Contaminant - A dust, fume, gas, mist, odor, smoke, vapor, soot, pollen, carbon, acid or particulate matter or any combination thereof.

Air Mass - A widespread body of air having approximately the same characteristics of temperature and moisture content throughout its horizontal extent. In addition, the vertical variations of temperature and moisture are approximately the same over its horizontal extent.

Air Pollution - The general term alluding to the undesirable addition to the atmosphere of substances (gases, liquids, or solid particles) either that are foreign to the 'natural' atmosphere or are in quantities exceeding their natural concentrations.

Air Pollution Alert - A statement issued by an Air Quality Regulatory Agency due to high *measured* concentrations of pollutants. The alert remains in effect until monitoring shows a decrease in pollutant levels. Should conditions worsen, air pollution warnings and emergencies may be issued. At each stage (alert, warning and emergency) additional emission restrictions are put into effect so as to not exacerbate the situation. Essentially, at the emergency level all industrial activities and auto usage stops. See Air Stagnation Advisory.

Air Pollution Potential - The relative ability of the atmosphere to dilute and transport pollutants. A high potential per unit of pollution results from low dilution rates and little transport by the wind. See Atmospheric Stability.

Air Quality - The composition of air with respect to quantities of pollution therein; used most frequently in connection with "standards" of maximum acceptable pollutant concentrations. Used instead of "air pollution" when refering to programs.

Air Quality Maintenance Area (AQMA) - An area that has been identified by an Air Quality Regulatory Agency to have the potential for exceeding any federal or state ambient air quality standard due to projected growth and development. See Nonattainment Area.

Air Quality Model - Mathematical or quantitative representation or simulation of air quality processes, e.g. emission models, receptor models or air quality dispersion models. See Model.

Air Stagnation Advisory (ASA) - A statement issued by a National Weather Service Forecast Office when atmospheric conditions are stable enough such that the *potential* exists for air pollutants to accumulate in a given area. The statement is initially issued when conditions are expected to last for at least 36 hours. See Air Pollution Alert.

Ambient Air - Literally, the air moving around us; the air of the surrounding outside environment.

Anticyclone - (High Pressure Ridge) An area of high atmospheric pressure with closed anticyclonic circulation. Anticyclonic flow is clockwise. See Surface High.

Area Source - A source category of air pollution that generally extends over a large area. Prescribed burning, field burning, home heating, and open burning are examples of area sources. See Point Source, Source.

Atmospheric Stability - The degree to which vertical motion in the atmosphere is enhanced or suppressed. Vertical motions and pollution dispersion are enhanced in an unstable atmosphere. A stable atmosphere suppresses vertical motion and limits pollution dispersion. See also Air Pollution Potential, Inversion, Stable Layer of Air.

Available Fuel - The portion of the total combustible material that fire will consume under given conditions. This could be duff, woody, herbaceous or litter.

Backing Fire - A fire spreading against the wind or downhill. Flames tilt away from direction of spread.

Clean Air Act - A federal law enacted to insure that air quality standards are attained and maintained. Initially passed by Congress in 1963, it has been amended several times, the latest being August of 1977.

Cold Front - The leading edge of a relatively cold air mass which moves in such a way that cold air displaces warmer air. The heavier cold air causes some of the warm air to be lifted. If the lifted air contains enough moisture, cloudiness, precipitation and even thunderstorms may result. In case both air masses are dry there may be no cloud formation.

Cold Trough - See Upper Level (Cold) Trough.

Convection Column - That portion of a smoke plume sharply defined by the buoyant forces of heated air and effluents.

Convective-lift Fire Phase - The phase of a fire when most of the emissions are entrained into a definite convection column.

Convergence - The term for horizontal air currents merging together or approaching a single point, such as at the center of a low pressure area producing a net inflow of air. The excess air is removed by rising air currents. Expansion of the rising air above a convergence zone results in cooling, which in turn often gives condensation (clouds) and sometimes precipitation. See Surface Low, Upper Level (Cold) Low, and Divergence.

Criteria Pollutants - Those air pollutants designated by the Environmental Protection Agency as potentially harmful and for which ambient air standards have been set to protect the public health and welfare. The criteria pollutants are carbon monoxide, sulfur dioxide, particulate, nitrogen dioxide, ozone, hydrocarbons and lead.

Cyclone - Loosely, a low pressure with counter-clockwise flow. On a very small scale the term is frequently misused to describe tornadoes. See Surface Low.

Deepening - A decrease in the central pressure of a low. This is usually accompanied by intensification of the cyclonic circulation (counter-clockwise wind flow around the low). See Filling.

Designated Area - Those areas identified as principal population centers or other areas requiring protection under state or federal air quality laws or regulations.

Dispersion - In air pollution terminology, loosely applied to the removal (by whatever means) of pollutants from the atmosphere over a given area; or the distribution of a given quantity of pollutant throughout a volume of atmosphere.

Disturbance - A weather system usually associated with clouds, rain and/or wind. See Impulse, Surface Low and Storm Center.

Divergence - The expansion or spreading out of a horizontal wind field. Generally associated with high pressure and light winds.

Drift Smoke - Smoke in evidence after all fire in the fuel has been extinguished. Generally considered to be the smoke lingering in an area or the smoke transported downwind which cannot be traced back to the burn site by tracking the main plume. See Residual Smoke, Plume.

Eddy - Any circulation drawing its energy from a flow of much larger scale, and brought about by pressure irregularities as in the downwind (lee) of a solid obstacle. Small scale eddies produce turbulent conditions.

Effluent - The mixture of substances, gases and liquids, and suspended matter, discharged into the environment as the result of a given process. Generally associated with water discharges. See Emission.

Emission - A release into the outdoor atmosphere of air contaminants. See Effluent.

Emission Factor (EFp) - The mass of particulate matter produced per unit mass of fuel consumed (pounds per ton, grams per kilogram).

Emission Inventory - A listing by source of the amounts of air pollutants discharged into the atmosphere.

Emission Rate - The amount of smoke produced per unit of time (lb/min). Emission Rate = Available Fuel x Burning Rate x Emission Factor.

Emission Standard - Limitation on the release of a contaminant or multiple contaminants to the ambient air from a single source.

Episode (Pollution) - A condition of poor contaminant dispersion which may result in concentrations considered potentially harmful to health or welfare. Episodes may also occur during periods of fairly good dispersion if the source of air contaminants is extremely large.

Filling - An increase in the central pressure of a low. Counter-clockwise wind flow around the low usually decreases as filling occurs. See Deepening.

Fine Particulate Matter - "Fine" particulates are those particles less than 10-15 microns in size. Fine particles have longer residence time in the atmosphere, are more harmful to health and have greater impact on visibility than larger particles. "Inhalable particulate" matter are those particles less than 10 microns in diameter. "Respirable particulate" matter are those particles less than 2.5 microns in size. Respirable particulates have an especially long residence time in the atmosphere and penetrate deeply into lungs. Particles from smoke are primarily in the respirable size range. Aerosol is often used interchangeably for the smaller airborne particulate matter. However, aerosols are more precisely defined as particles in a gaseous medium. See Particulate Matter, PM-10 and Aerosol.

Firing Technique - A method of igniting an area to consume the fuel in a prescribed pattern; e.g., heading or backing fire, spot fire, strip-head fire, and ring fire.

Fuel Loading - The amount of fuel present expressed quantitatively in terms of weight of fuel per unit area. This may be available fuel or (consumable fuel) total fuel and is usually dry weight.

Fuel Type - An identifiable association of fuel elements of distinctive species, form, size, arrangement, or other characteristics, that will cause a predictable rate of fire spread or difficulty of control, under specified weather conditions.

Heading Fire - A fire spreading with the wind or uphill. Flames tilt in the direction of the spread.

Heat Low - (Heat Trough, Thermal Low, Thermal Trough) An area of low pressure caused by intense heating of the earth's surface. High surface temperature causes air to expand and rise, resulting in low atmospheric pressure and induces a weak inflow of air at the surface. Air which rises in a heat low is very dry so clouds seldom form. Rising air above a heat low produces a warm Upper Level High and results in a net outflow of air aloft. Heat lows remain practically stationary over areas which produce them.

Heat Release Rate to the Atmosphere - The amount of heat released to the atmosphere during the combustion stage of a fire per unit of time.

Heat Trough - (Heat Low, Thermal Low, Thermal Trough) A *Heat Low* which is elongated in shape.

High Pressure Aloft - See *Upper Level High*

High Pressure Ridge - (Surface High, Area of High Pressure, Surface Ridge) An elongated area of relatively high atmospheric pressure. If the term aloft or upper level is not used it should be assumed that reference is to a surface system. The opposite of Ridge is a Trough. See *Surface High, Low Pressure Trough.*

Hydrocarbons - A general term for organic compounds that contain only carbon and hydrogen in the molecule. They are divided into saturated and

and aromatic (benzene) hydrocarbons. In photochemical pollution they react with atomic oxygen and ozone to form new reactive compounds

Impulse - A term used in weather primarily to describe a weak disturbance that does not necessarily have an associated *Storm Center* or *Surface Low.* The disturbance usually does not create severe weather and is frequently associated with a *Marine Air Push.*See *Wave, Surface Low.*

Intrusion - See *Smoke Intrusion.*

Inversion - An increase of temperature with height in the atmosphere. Vertical motion in the atmosphere is inhibited allowing for pollution buildup. A "normal" atmosphere has temperature decreasing with height. See also *Atmospheric Stability, Air Pollution Potential, Stable Layer of Air, Temperature Inversion.*

Low Aloft - See *Upper Level (Cold) Low.*

Low Pressure Trough - (Surface Low, Low Pressure System, Disturbance, Storm Center) An elongated area of relatively low atmospheric pressure. If the term aloft If the term aloft or upper level is not used it should be assumed that reference is to a surface trough. As in the case of a *Surface Low,* rising air often causes cloudiness in a trough area. While a Surface Low can be assumed to have a complete (closed) counter-clockwise circulation around it, a trough may be open at one end. That is, a trough may be an elongated portion of a larger low pressure system.

Maritime Air - (Ocean Air, Maritime Air) Air which has assumed high moisture content and the temperature characteristics of a water surface due to extensive exposure to that surface.

Micron - One millionth of a meter, a micrometer.

Mixing - A random exchange of air parcels on any scale from the molecular to the largest eddy.

Mixing Height - Measured from the surface upward, the height to which relatively vigorous mixing due to convection occurs. Same as *mixing depth.* Use of this term normally implies presence of an inversion and the base of the inversion is the top of the mixed layer and defines the mixing height.

Mixed or Mixing Layer - That portion of the atmosphere from the surface up to the mixing height. This is the layer of air, usually a sub-inversion layer, within which pollutants are mixed by turbulence and diffusion.

Model - A quantitative and mathematical representation or simulation which attempts to describe the characteristics or relationships of physical events. See Air Quality Model

National Ambient Air Quality Standards (NAAQS) - A legal limit on the level of atmospheric contamination. The level is established as the concentration limited needed to protect all of the public against adverse effects on public health and welfare, with an adequate safety margin. Primary standards are those related to health effects. Secondary standards are designed to protect the public welfare from effects such as visibility reduction, soiling, material damage and nuisances.

Non-convective-lift Fire Phase - The phase of a fire when most emissions are not entrained into a definite convective column.

Nonattainment Area - An area identified by an Air Quality Regulatory Agency through ambient air monitoring (and designated by the Environmental Protection Agency), that presently exceeds Federal ambient air standards. See Air Quality Maintenance Area.

Offshore Flow - Wind blowing from land to water.

Onshore Flow - Wind blowing from water to land.

Particulate Matter - Any liquid or solid particles. "Total suspended particulates" as used in air quality are those particles suspended in or falling through the atmosphere. They generally range in size from 0.1 to 100 microns.

Particulate Mass Concentration - The amount of particulate matter per unit volume of air usually expressed as micrograms per cubic meter (ug/m^3).

Perturbation - Any departure introduced into an assumed steady state of a system. See Disturbance, Impulse

Photochemical Process - The chemical changes brought about by the radiant energy of the sun acting upon various substances. The products are known as photochemical pollutants.

Photochemical Pollutant - Any pollutant produced by photochemical reactions. The most common photochemical pollution involves the ultraviolet portion of sunlight, nitrogen dioxide and certain hydrocarbons. A wide variety of new products are produced, including ozone, and these in turn react to produce other products. Many are harmful to plants and animals.

Plume - The segment of the atmosphere occupied by the emissions from a single source or a grouping of sources close together. A convection column, if one exists, forms a specific part of the plume.

PM-10 - Particles with an aerodynamic diameter smaller than or equal to a nominal ten micrometers.

Point Source - A permanent source of air pollution that can be distinctly identified such as a smokestack. See Area Source, Source.

Pollutant - With respect to the atmosphere, any substance within it that is foreign to the natural atmosphere or that exceeds its natural concentrations in the atmosphere. The universal connotations is that a pollutant is potentially deleterious.
See Air Contaminant.

Prescribed Burning - Controlled application of fire to wild land fuels in either their natural or modified state, under such conditions of weather, fuel moisture, soil moisture, etc., as allows the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to further certain planned objectives of silviculture, wildlife habitat management, grazing, fire hazard reduction, etc.

Pressure Gradient - The difference in atmospheric pressure between two points on a weather map. That is, the magnitude of pressure difference between two points at sea level, or at constant elevation above sea level. Wind speed is inversely related to pressure gradient. If distance between constant pressure lines is reduced by one-half, wind speed will be doubled. Conversely, if distance between lines is doubled, wind speed will be reduced by one-half.

Pressure Pattern - The distribution of surface atmospheric pressure features over an area of the earth as shown on a weather map. Surface pressure features include lines of constant pressure (isobars), highs, lows, and pressure gradient. The pressure pattern is directly related to wind speeds and directions

Prevention of Significant Deterioration (PSD) - A program identified by the Clean Air Act to prevent air quality and visibility degradation and to remedy existing visiblity problems. Areas of the country are grouped into 3 classes which are allowed certain degrees of pollution depending on their uses. National Parks and Wilderness Areas meeting certain criteria are "Class 1" or "clean areas" in that they have the smallest allowable increment of degradation.

Regional Haze - A haze over large area with no attributable source.

Residual Combustion Stage - The smoldering zone behind the zone of an advancing fire front.

Residual Smoke - Smoke produced after the initial fire has passed through the fuel. See Drift Smoke.

Respirable Suspended Particulate Matter (RSP) - See Particulate Matter, Fine Particulates, PM-10.

Ridge - See High Pressure Ridge.

Ridge Aloft - See Upper Level Ridge and Upper Level High.

Smog - Generally considered only photochemical air pollution. Originally meant a combination of smoke and fog.

Smoke Intrusion - Smoke from prescribed fire entering a designated area at unacceptable levels.

Smoke Management - Conducting a prescribed fire under fuel moisture and meteorological conditions, and with firing techniques that keep the smoke's impact on the environment within acceptable limits.

Smoke Vent Height - Level, in the vicinity of the fire, at which the smoke ceases to rise and moves horizontally with the wind at that level.

Smoldering Phase - The overall reaction rate of the fire has diminished to a point at which concentrations of combustible gases above the fuel is too low to support a persistent flame envelop. Consequently the temperature drops and gases condense. The smoke evolved during this phase is virtually soot-free, consisting mostly of tar droplets less than a micrometer in size.

Sounding - (Upper Air Sounding, Radiosonde) A sampling of upper air conditions made by means of instruments and a small radio transmitter on a free balloon. Automatic radio signals originated by action of weather instruments are sent to a ground receiver. These signals are interpreted for use in analyzing and predicting upper air conditions over a wide area of the earth. Weather elements determined at a number of altitude points as the balloon rises are temperature, atmospheric moisture, pressure, wind direction and speed. Similar sounding may be made using fixed balloons or tethersondes.

Source - A point, line, or area, at which mass or energy is added to a system, either instantaneously or continuously. Conversely, at a sink, mass or energy is removed. Examples of sources in the context of air pollution are as follows: a smoke stack is a point source; a freeway is a line source; field or slash burning are area sources.

Split Flow - A divergent wind field. Storms moving into a split flow field tend to lose strength. Winds are generally light in such a flow field. See Divergence.

Stable Layer of Air - A layer of air having a temperature change (lapse rate) or less than dry adiabatic (approximately -5.4 degrees F per 1,000 feet) thereby retarding either upward or downward mixing of smoke.

State Implementation Plan (SIP) - A plan required by the Clean Air Act and prepared by an Air Quality Regulatory Agency, which describes how the state will attain and maintain air quality so as to not violate National Ambient Air Quality Standards.

Storm Center - The central point or area of a weather system associated with increased winds, clouds or precipitation (or any combination thereof).

Subsidence - Downward or sinking motion of air in the atmosphere. Subsiding air warms due to compression. Increasing temperature and decreasing humidities are present in subsiding air. Subsidence results in a stable atmosphere inhibiting dispersion.

Subsidence Inversion - An inversion caused by sibsiding air often resulting in very limited atmospheric mixing conditions. See Subsidence.

Surface High - (High, High Pressure System, High Pressue Ridge) An area on the earth's surface where atmospheric pressure is at a relative maximum. Winds at weather stations blow clockwise around highs in the Northern Hemisphere but, due to friction with the earth's face, tend to cross constant pressure lines away from the high center. Air is usually subsiding within a surface high. This causes warming due to air compression. This, in turn, results in stable atmospheric conditions and light surface winds.

Surface Low - An area on the earth's surface where atmospheric pressure is at a relative minimum. Winds at weather stations blow counter-clockwise around lows in the Northern Hemisphere but, due to friction with the earth's surface, tend to cross constant pressure lines toward the low center. Upon converging at the low center, air currents are forced to rise. As air rises it cools due to expansion. Cooling reduces its capacity to hold moisture; so cloudiness and precipitation are common in lows. If a low center intensifies sufficiently it will take on the characteristics of a storm center with precipitation and strong winds.

Synergism - The cooperative action of separate substances which, together, have greater total effect than the sum of their individual effects.

Synoptic - Literally, at one time. Thus, in meteorological useage the weather conditions over an area at a given point in time.

Temperature Inversion - Often shortened to just "inversion". See Inversion.

Thermal Low - See Heat Low.

Thermal Trough - See Heat Trough and Heat Low.

Total Suspended Particulate Matter (TSP) - See Particulate Matter, PM-10, Fine Particulate Matter.

Toxic - Relating to a harmful effect by a poisonous substance on the human body by physical contact, ingestion, or inhalation.

Transport Wind Speed - A measure of the average rate of the horizontal transport of air within the *Mixing Layer.* May also be the wind speed at the final height of plume rise. Generally refers to the rate at which emissions will be transported from one area to another. See Mixing Layer.

Trough - See Low Pressure Trough.

Trough Aloft - See Upper Level (Cold) Trough.

Turbulence - A complex spectrum of fluctuating, disordered motion superimposed on the mean flow of a liquid or gas.

Upper Level (Cold) Low - (Upper Level Disturbance, Cold Low Aloft) A circulation feature of the upper atmosphere where pressure, at a constant altitude, is lowest. Winds blow counter-clockwise around the center in an approximately circular pattern. Upper level lows are usually quite small. The mechanics of these upper lows is such that a pool of cool moist air always accompanies their development. There is often no evidence of low pressure at the earth's surface. An upper low may exist above a surface high pressure system.

Upper Level (Cold) Trough - (Trough, Trough Aloft, Upper Level (Cold) Low) An elongated area of relatively low pressure, at constant altitude, in the atmosphere. The opposite of an upper level ridge. Upper level troughs are usually oriented north-south, with the north end open. That is, air currents moving from west to east around the earth flow around three sides of the trough then turn eastward rather than toward the west, as in the case of a closed circulation. A large upper level trough may have one or more small upper level closed low circulation systems within it.

Upper Level High - (Upper High, High Aloft, Upper Level Ridge) A circulation feature of the upper atmosphere where pressure, at a constant altitude, is higher than in the surrounding region. Winds blow clockwise around an upper level high. Air in an upper level high is usually subsiding. This results in comparatively warm dry air with light winds over a large area. An upper level high may exist without there being high pressure at the earth's surface.

Upper Level Ridge - (Upper Level High, Ridge Aloft) An elongated area of relatively high pressure, at a constant altitude, in the atmosphere. The opposite of an upper level trough. Upper level ridges are often oriented north-south, altering between upper level troughs, however, during summer they may assume random orientations and vast dimensions. See Upper Level High.

Volatile Organic Compounds - Generally considered to be those hydrocarbon compounds which have a high potential for reactivity and which actively participate in photochemical reactions. Examples are gasoline and solvent vapors.

Warm Front - The leading edge of a relatively warm air mass which moves in such a way so that warm air displaces colder air. Winds associated with warm frontal activity are usually light and mixing is limited. The atmosphere is relatively stable when compared to cold front activity. See Cold Front.

Wave - A disturbance that transfers energy from point to point and may take the form of a deformation of pressure or temperature. In the atmosphere such disturbances may result in major storms or merely result in changes in cloud, wind and temperature conditions. Development of a wave on a front usually slows the advance of the front due to transfer of energy to the wave development and movement. See Impulse.

Wind Shear - A variation in wind speed and/or direction in a layer of the atmosphere or between layers. The variation may be in the horizontal or vertical and may result in significant turbulence depending upon the magnitude of the wind speed/direction differences. A strong *Wind Shear* may act like an inversion and inhibit plume rise. It may also fracture the smoke plume, not allowing smoke to rise much above terrain levels. A strong horizontal anticyclonic shear results in downward motion and may bring smoke aloft to the surface. See Anticyclonic.

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